

The strangeness form factors of the proton within nonrelativistic constituent quark model revisited

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Abstract

We reexamine, within the nonrelativistic constituent quark model (NRCQM), a recent claim that the current data on the strangeness form factors indicates that the $uuds\bar{s}$ component in the proton is such that the $uuds$ subsystem has the mixed spatial symmetry $[31]_X$ and flavor spin symmetry $[4]_{FS}[22]_F[22]_S$, with \bar{s} in S state (configuration I). We find this claim to be invalid if corrected expressions for the contributions of the transition current to G_A^s and G_E^s are used. We show that, instead, it is the lowest-lying $uuds\bar{s}\bar{s}$ configuration with $uuds$ subsystem of completely symmetric spatial symmetry $[4]_X$ and flavor spin symmetry $[4]_{FS}[22]_F[22]_S$, with \bar{s} in P state (configuration II), which could account for the empirical signs of all form factors G_E^s , G_M^s , and G_A^s . Further, we find that removing the center-of-mass motion of the clusters will considerably enhance the contributions of the transition current. We also demonstrate that it is possible to give a reasonable description of the existing form factors data with a tiny probability $P_{s\bar{s}} = 0.025\%$ for the $uuds\bar{s}\bar{s}$ component. We further see that with a small admixture of configuration I, the agreement of our prediction with the data for G_A^s at low- q^2 region can be markedly improved. We find that without removing CM motion, $P_{s\bar{s}}$ would be overestimated by about a factor of four in the case when transition current dominates. We also explore the consequence of a recent estimate reached from analyzing the existing data on $\bar{d} - \bar{u}$, $s + \bar{s}$, and $\bar{u} + \bar{d} - s - \bar{s}$, that $P_{s\bar{s}}$ lies between 2.4 – 2.9%. It would lead to a large size for the five-quark system and a small bump in both $G_E^s + \eta G_M^s$ and G_E^s in the region of $q^2 \leq 0.1 \text{ GeV}^2$ within the considered model.

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The first indications of possible existence of strangeness content in the proton came from deep-inelastic muon scattering, elastic neutrino-proton scattering, and analyses of πN σ -term [1]. Many other observables were later suggested, including excess ϕ production in $p\bar{p}$ annihilation [2], double polarizations in photo- and electroproduction of ϕ meson [3], and asymmetry in scattering of longitudinally polarized electrons from polarized targets. While the measurement of double polarization in ϕ photoproduction is being pursued with the development of polarized HD target by LEPS at SPring-8 [4], four vigorous experimental programs SAMPLE [5], HAPPEX [6], A4 [7], and G0 [8] have already been undertaken to measure parity-violating asymmetry of polarized electron-proton scattering in order to extract proton strangeness electromagnetic form factors.

On the theoretical side, lattice QCD remains the only theoretical method which could provide a reliable determination of the strangeness form factors from the first principle. For example, a recent low-mass quenched lattice QCD simulation, with the use of chiral extrapolation technique and the assumption of charge symmetry, gives $\mu_S = (-0.046 \pm 0.019)\mu_N$ [9] and $G_E^s(Q^2 = 0.1 \text{ GeV}^2) =$

$-0.009 \pm 0.005 \pm 0.003 \pm 0.027$ [10]. More recent LQCD efforts can be found in Ref. [11]. Nevertheless, a study of this intriguing question within hadron models could still provide invaluable insight concerning the underlying quark structure, e.g., how the strange quarks are arranged inside proton.

Recently, Zou and Riska [12] considered the possible low-lying configurations of the $uuds\bar{s}\bar{s}$ component of the proton within a constituent quark model. It was concluded that the empirical indications of a positive strangeness magnetic moment of the proton [5, 6, 7] suggest that the dominant $s\bar{s}$ configuration in the proton would have the \bar{s} in the ground state and $uuds$ system in the P state. It would lead to an interesting implication that the $qqqq\bar{q}$ components in the proton would mainly be in colored quark cluster configurations rather than in "meson cloud" configurations as commonly perceived. The calculation of Ref. [12] was later extended to the evaluation of proton strangeness form factors [13, 14].

The calculation of Refs. [12, 13, 14] did not remove the center-of-mass (CM) motion of the quark clusters. That could conceivably affect the estimate of the probability of the $s\bar{s}$ configuration from the measured strangeness mag-

netic moment considerably, as proposed in Ref. [12]. Accordingly, we set forth to reexamine the problem with the removal of the CM motion of the clusters. In the process, we obtained results which differ substantially from those presented in Refs. [12, 13, 14] where the CM motion was not removed.

The configurations of the $uuds\bar{s}$ component in the proton considered in Refs. [12, 13, 14] are all of (4,1) clustering type in that either four quarks $uuds$ would be in P state with \bar{s} in S state (configuration I) or $uuds$ in S state while \bar{s} in P state (configuration II), respectively, in order to ensure $uuds\bar{s}$ as a whole has positive parity as proton. The symmetry of the spatial state of the four-quark system in configurations I and II would then be of $[31]_X$ and completely symmetric $[4]_X$, respectively. Within the harmonic oscillator constituent quark model, these two configurations are degenerate and of the lowest energy. However, the degeneracy is lifted by the color hyperfine quark-quark interaction as shown in Ref. [12]. After the splitting, the states of the lowest energy in configurations I and II for $uuds$ cluster would have the flavor and spin state symmetry of $[4]_{FS}[22]_F[22]_S$ and $[31]_{FS}[211]_F[22]_S$, respectively [12]. We will focus only on these two states of the lowest energy in this study.

The calculation of the strangeness form factors G_E^s , G_M^s , and G_A^s within a harmonic oscillator constituent quark model is straightforward. However, the evaluation of the contribution of the transition current is involved if the CM motion is to be removed.

We first compare our results for the form factors with those obtained in Ref. [13] where the CM motion is not removed. In order to facilitate the comparison, we will follow the notations and conventions of Refs. [13, 14] as much as possible, unless otherwise specified.

There are already some differences between our results and those given in Ref. [13] for the simple case of diagonal matrix elements of the vector and axial vector current operators. Besides the factor of $\sqrt{1+q^2/4m_s^2}$ introduced in the denominators for G_E^s and G_M^s to account for relativistic effects, we have not been able to reproduce the factor of $(1-q^2/18\omega_5^2)$ (we use ω_5 to denote the harmonic oscillator parameter associated with the $uuds\bar{s}$ component so our ω_5 is ω used in [13]) which appears in the expression for G_M^s . However, those differences are numerically insignificant in the low- q^2 region where the nonrelativistic model calculations are, at best, expected to be valid.

For the contribution of transition current, i.e., the non-diagonal matrix elements of the currents between $3q$ and $5q$ states, there are three discrepancies between our results and those of Ref. [13]. First, there is a sign difference for G_E^s , as well as that our result for G_M^s is $\sqrt{3}$ times larger than that presented in Ref. [13], which arises from a simple evaluation of the color matrix element [15]. The last and the most serious difference lies within G_A^s in which we obtain the following expression for the contribution of

transition current to G_A^s

$$G_A^{s,ND}(q^2) = \delta \frac{g_s}{g_p} C_{35} \frac{2\alpha_s}{m_s} e^{-q^2/4\omega_5^2} \sqrt{P_{uud} P_{s\bar{s}}}, \quad (1)$$

where the superscript ND specifies that it is a non-diagonal matrix element. The parameters ω_3 , P_{uud} and ω_5 , $P_{s\bar{s}}$ denote the usual oscillator parameters and probabilities, respectively, of the uud and $uuds\bar{s}$ configurations in the proton, and $C_{35} \equiv (2\omega_3\omega_5/(\omega_3^2 + \omega_5^2))^{9/2}$, while δ denotes the relative phase between the uud and $uuds\bar{s}$ components of the wave functions in the proton. Eq. (1) approaches constant at $q^2 = 0$, while the corresponding result of Ref. [13] contains a factor of q^2 and hence vanishes at $q^2 = 0$. Since, as we see later, the contributions of non-diagonal matrix elements would dominate over the diagonal ones for all reasonable choices of ω_3 and ω_5 , our result of Eq. (1) would lead to a consequence that G_M^s and G_A^s would be of the same sign, irrespective of the choice of phase δ , at low- q^2 region which is in contradiction with the existing experimental data. It would then exclude the possibility that configuration I with four quarks $uuds$ in P state and \bar{s} in S state could be the dominant configuration for the $uuds\bar{s}$, as concluded in Ref. [13]. We have carried out a direct numerical six-dimensional integration to verify that results agree with the analytical expression of Eq. (1) numerically.

When the center-of-mass motion of the five-quark ($5q$) cluster is removed, we obtain the following results, in the case of configuration I, for the contributions of the diagonal matrix elements of the current to the proton strangeness form factors.

$$G_E^{s,D}(q^2) = -\frac{q^2}{24\omega_5^2} e^{-q^2/5\omega_5^2} P_{s\bar{s}}, \quad (2)$$

$$G_M^{s,D}(q^2) = \frac{m_p}{2m_s} e^{-q^2/5\omega_5^2} P_{s\bar{s}}, \quad (3)$$

$$G_A^{s,D}(q^2) = -\frac{1}{3} e^{-q^2/5\omega_5^2} P_{s\bar{s}}, \quad (4)$$

where the superscript D indicates that they are the diagonal matrix elements. Without the removal of the CM motion of the $5q$ cluster, the Gaussian factor $e^{-q^2/5\omega_5^2}$ in Eqs. (2-4) would become $e^{-q^2/4\omega_5^2}$. This means that the removal of CM motion causes the form factors to decrease more slowly. Our results for the transition ($3q - 5q$) and ($5q - 3q$) contributions to the strangeness form factors, when the CM of $3q$ and $5q$ clusters are removed read as

$$G_E^{s,ND}(q^2) = \delta C_{35}^{2/3} \frac{2 \cdot 15^{3/4}}{9\sqrt{3}} \frac{q^2}{m_s \omega_5} e^{-4q^2/15\omega_5^2} \times \sqrt{P_{uud} P_{s\bar{s}}}, \quad (5)$$

$$G_M^{s,ND}(q^2) = \delta C_{35}^{2/3} \frac{2 \cdot 15^{3/4}}{9\sqrt{3}} \frac{4m_p}{\omega_5} e^{-4q^2/15\omega_5^2} \times \sqrt{P_{uud} P_{s\bar{s}}}, \quad (6)$$

$$G_A^{s,ND}(q^2) = \delta C_{35}^{2/3} \frac{2 \cdot 15^{3/4}}{9\sqrt{3}} \frac{3\omega_5}{m_s} e^{-4q^2/15\omega_5^2} \times \sqrt{P_{uud} P_{s\bar{s}}}. \quad (7)$$

One observes that the exponents of the Gaussians in Eqs. (2-4) and Eqs. (5-7) are different. This is expected since the center of masses of the $3q$ and $5q$ clusters are also different. It is interesting to see that the transition current contributions drop faster than the diagonal ones. Furthermore, it is seen that $G_M^{s,ND}$ and $G_A^{s,ND}$ are of the same sign as is the case before the removal of the CM motion, independent of the relative phase between the wavefunctions of $3q$ and $5q$ components. Consequently, as long as the transition current contributions dominate over the direct terms, then the configuration with \bar{s} in S state cannot be the dominant configuration for $uudss\bar{s}$ component.

We next study configuration II which is degenerate with the lowest energy configuration I before being lifted by the color hyperfine quark-quark interaction. In configuration II, $uuds$ cluster is in S state while \bar{s} is in P state. Only the results with the removal of CM motion will be presented. The direct current gives rise to the following contributions,

$$G_E^{s,D}(q^2) = \frac{q^2}{8\omega_5^2} e^{-q^2/5\omega_5^2} P_{s\bar{s}} \quad (8)$$

$$G_M^{s,D}(q^2) = \frac{m_p}{m_s} \left(\frac{-1}{6} - \frac{2q^2}{15\omega_5^2} \right) e^{-q^2/5\omega_5^2} P_{s\bar{s}} \quad (9)$$

$$G_A^{s,D}(q^2) = \left(\frac{-1}{3} + \frac{2q^2}{15\omega_5^2} \right) e^{-q^2/5\omega_5^2} P_{s\bar{s}}. \quad (10)$$

The results for the transition current matrix elements between ($3q - 5q$ and $5q - 3q$) read as follows,

$$G_E^{s,ND}(q^2) = \delta C_{35}^{2/3} \left(\frac{2}{5} \right)^{1/2} \left(\frac{5}{3} \right)^{3/4} \frac{q^2}{m_s \omega_5} \times e^{-4q^2/15\omega_5^2} \sqrt{P_{uud} P_{s\bar{s}}}, \quad (11)$$

$$G_M^{s,ND}(q^2) = \delta C_{35}^{2/3} \left(\frac{2}{5} \right)^{1/2} \left(\frac{5}{3} \right)^{3/4} \frac{4m_p}{\omega_5} \times e^{-4q^2/15\omega_5^2} \sqrt{P_{uud} P_{s\bar{s}}}, \quad (12)$$

$$G_A^{s,ND}(q^2) = -\delta C_{35}^{2/3} \left(\frac{2}{5} \right)^{1/2} \left(\frac{5}{3} \right)^{3/4} \frac{5\omega_5}{m_s} \times e^{-4q^2/15\omega_5^2} \sqrt{P_{uud} P_{s\bar{s}}}. \quad (13)$$

We see that the direct current contributions to G_M^s and G_A^s , as given in Eqs. (9-10), are both negative at $q^2 = 0$ which contradicts the experiments. However, the transition current contributions to G_M^s and G_A^s , as given in Eqs. (12-13) are of opposite sign and in agreement with the data, independent of the sign of δ . Since the transition current contributions dominate over the direct current contributions in the model considered here, it is hence of interest to see whether we could fit the experimental data of the proton strangeness form factors with configuration II or some linear combinations of configurations I and II.

We take the proton and quark masses to be 0.938 and 0.313 GeV, respectively. The oscillator parameter for the $3q$ core is fixed to be $\omega_3 = 0.246$ GeV. We then vary the oscillator parameter ω_5 and the probability $P_{s\bar{s}}$ of the $5q$ component $uudss\bar{s}$, to fit the experimental data $G_E^s + \eta G_M^s$ [8], which are more directly measured in the experiments and G_A^s as extracted in Ref. [16] where its sign in low- q^2 region is well determined. Both signs of $\delta = \pm 1$ are tried and the best results are then determined.

Our best fits to the experimental data G_A^s and $G_E^s + \eta G_M^s$, within configuration II, are shown in Fig. 1 as solid curves, with $\omega_5 = 0.469$ GeV, $P_{s\bar{s}} = 0.025\%$, and relative phase $\delta_P = +1$, where subscript P refers to the fact that the configuration under consideration has \bar{s} in P state. The data denoted with open circles are from Ref. [8] and the crosses represent the corresponding values after the two-boson exchange effects are corrected [17]. Solid triangles are the data from HAPPEEx [6] and open boxes are from Ref. [16]. The ensuing results for G_E^s and G_M^s are shown in Fig. 2. It is seen that the agreement with the data are in general quite good except for $G_E^s + \eta G_M^s$ and G_M^s at small values of q^2 , where there are large experimental uncertainties.

We have also explored the possibility of mixing configurations II and I, namely,

$$|\text{proton}\rangle = A_3 |3q\rangle + A_5 \sum_{\alpha=S,P} \delta_\alpha b_\alpha |5q; \alpha\rangle, \quad (14)$$

where $|5q; \alpha\rangle$ and δ_α denote the $uudss\bar{s}$ states with \bar{s} in either S or P states and its relative phase with the three-quark state $|3q\rangle$, respectively, to see whether a better description of the data can be obtained. It turns out that some improvements can be achieved only for G_A^s at low- q^2 region with a small mixing probability of $b_S^2 = 8\%$ for configuration I, relatives phases $\delta_P = 1$, $\delta_S = -1$, and a combined probability of $P_{s\bar{s}} = A_5^2 = 0.058\%$ (called admixture A), as shown by the dashed curves in Figs. 1 and 2.

It is seen that we could fit the data reasonably well with a rather small probability of $uudss\bar{s}$ component, e.g., $P_{s\bar{s}} = 0.025\% \sim 0.058\%$ with either configuration II alone or a mixture of configurations II and I. It is in sharp contrast to the values of $P_{s\bar{s}} = 10 \sim 15\%$ required in Ref. [13] in order to fit G_M^s . Such a great reduction in $P_{s\bar{s}}$ needed to reproduce the experimental data on the strangeness form

Table 1: The strangeness magnetic dipole moment μ_s (in unit of μ_N), strangeness contribution to proton spin ΔS , and the radius of the $uud\bar{s}\bar{s}$ component, obtained in our calculation, with \bar{s} in pure P state, S and P states admixture A, and B , as compared with the experiments.

	\bar{s} in P state (0.025%)	\bar{s} in S and P admixture A (0.058%)			\bar{s} in S and P admixture B (2.4%)			Experiments
		S state (8%)	P state (92%)	Total	S state (15%)	P state (85%)	Total	
μ_s	0.066	-0.030	0.096	0.066	-0.80	1.80	1.01	0.37 ± 0.79 [18]
ΔS	-0.062	-0.017	-0.090	-0.107	-0.025	-0.097	-0.12	-0.10 ± 0.03 [19]
r_{5q}	0.5 fm			0.5 fm			2.16 fm	N/A

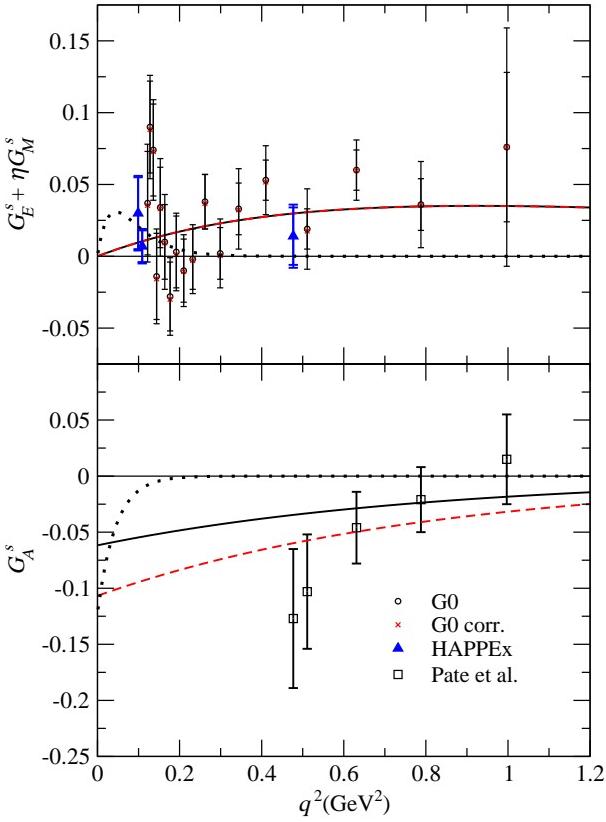


Figure 1: Our predictions for form factors $G_E^s + \eta G_M^s$ and G_A^s . The results obtained with configurations with \bar{s} in pure P state, S and P states admixture A, and B are denoted, respectively, by full, dashed, and dotted lines. Experimental data from Refs. [8, 6, 16] are denoted by open circles (G0), solid triangles (HAPPEX), and open boxes (Pate *et al.*), respectively, while the crosses are the corrected values of the G0 data by taking into account the two-boson exchange mechanism [17].

factors arises from several sources. These include the correction factor $\sqrt{3}$ in the evaluation of color matrix elements, change of the configuration for \bar{s} from S to P state, removal of the CM motion of the clusters, and the use of different model parameters. Each of them enhances the transition current matrix elements by $\sim 50 - 120\%$. It is interesting to note that our set of harmonic oscillator model parameters would give rise to a size of the $uud\bar{s}\bar{s}$ to be about 0.5 fm, which is quite close to that estimated

by Ref. [20] using a proton-core- ϕ picture for five-quark system with a scaling factor $s = 1.5$.

The corresponding results for strangeness magnetic moment μ_s , strangeness contribution to proton spin $\Delta S = G_A^s(0)$, and the size of $uud\bar{s}\bar{s}$ component r_{5q} , with \bar{s} in P state or admixture of S and P states, are given in Table 1 and compared with the experiments. The agreement between experiments and numbers obtained with \bar{s} in admixture of S and P states seems reasonable.

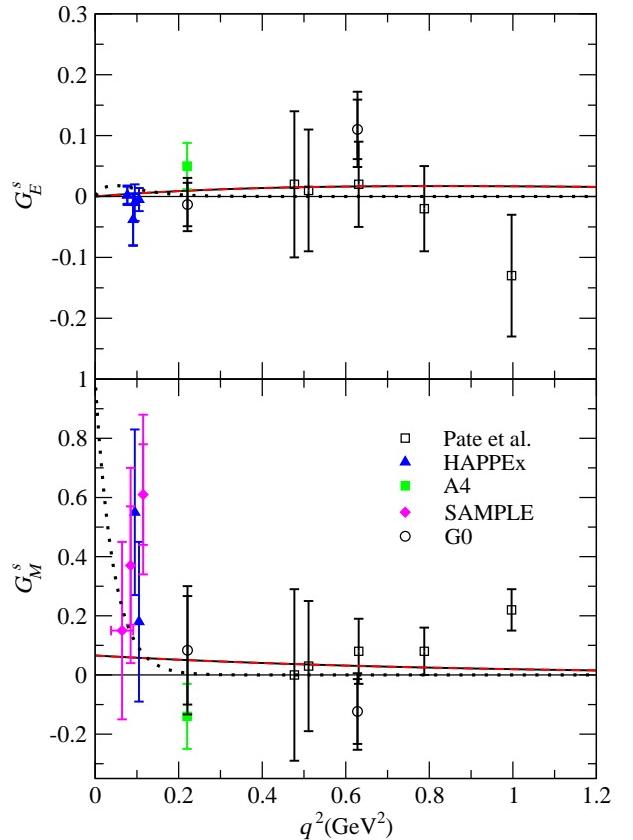


Figure 2: Our results for G_E^s and G_M^s . Notations are the same as in Fig. 1. Experimental data are from Refs. [5, 6, 7, 8] and denoted with solid diamonds (SAMPLE), solid triangles (HAPPEX), solid boxes (A4), and open circles (G0), respectively.

Recently, Chang and Peng [21] generalize the approach of Brodsky, Hoyer, Peterson, and Sakai (BHPS) [22] for the intrinsic charm quark distribution in the nucleons to

the light-quark sector involving intrinsic \bar{u} , \bar{d} , and \bar{s} sea quarks to analyze the existing $\bar{d}(x) - \bar{u}(x)$, $s(x) + \bar{s}(x)$, and $\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x)$ data and conclude that probability $P_{s\bar{s}}$ for five-quark configuration $uudss$ to lie between 0.024–0.029. We explore the consequence of such a result to our model calculation by fixing $P_{s\bar{s}} = 2.4\%$ and vary ω_5 to fit the data. The resultant fit we obtain with $\omega_5 = 0.108$ GeV, which corresponds to a large size of the five-quark system with $r_{5q} = 2.16$ fm, and a small admixture of S state with a probability of about 15% (called admixture B), are shown in Figs. 1 and 2 by dotted lines. The most interesting feature of this fit is the appearance of a bump in $G_E^s + \eta G_M^s$ in the very low- q^2 region with $q^2 \leq 0.1$ GeV 2 , which seems to be hinted by the G0 data but hampered by large experimental error bars and fluctuations. It would be worthwhile to carry out experiments in such a low- q^2 region if further theoretical study would support this behavior. All form factors vanish rapidly beyond $q^2 \geq 0.2$ GeV 2 because of the small value of ω_5 and Gaussian nature of the harmonic oscillator wavefunctions. We note that the predicted values of μ_s , ΔS , and r_{5q} , as presented in Table 1, agree with the data within experimental errors. However, the experimental value of 0.37 ± 0.79 was obtained in Ref. [18] in a fit to the form factors including the next-to-leading-order terms of the Q^2 -dependence. In another fit with only leading order in Q^2 which has almost same reduced χ^2 , a value of $\mu_s = 0.12 \pm 0.55 \pm 0.07$ was obtained which would disfavor configuration B.

In summary, we have reinvestigated, within a nonrelativistic constituent quark model, the question of whether a five-quark component with configuration of (4,1) clustering, as previously considered by Riska and Zou [12, 13] can account for the data of the proton strangeness form factors. Two configurations of the lowest energies, both consist of four quarks in colored state and one antiquark are considered. They possess spatial-flavor-spin symmetry $[31]_X - [4]_{FS}[22]_F[22]_S$ and $[4]_X - [31]_{FS}[211]_F[22]_S$, with antiquark \bar{s} in the S (configuration I) and P states (configuration II), respectively. They are degenerate before being splitted by the color hyperfine quark-quark interaction with configuration II of higher energy.

We have not been able to reproduce the results of Ref. [13] to substantiate their claim that configuration I is to be preferred as the dominant configuration of a possible five-quark component. The claim made in Ref. [13] is based on a particular choice of the relative phase δ between uud and $uudss$ components of the proton wave functions such that G_M^s could be positive at small q^2 region. However, the corrected expression of G_A^s we obtain for configuration I would lead to a G_A^s to be of the same sign as G_M^s in the low- q^2 region which clearly contradicts all existing data. We also find that the expression for the transition current contribution to G_E^s obtained in Ref. [13] carries an erroneous minus sign.

We then proceed to study configuration II, where \bar{s} is in P state, and make an effort to remove the CM motions of the clusters which was not done in Ref. [13]. We demon-

strate that it is possible to give a satisfactory description of the existing data on the proton strangeness form factors G_E^s , G_M^s , G_A^s , and the linear combination of $G_E^s + \eta G_M^s$ which is more directly extracted from the parity-violating asymmetry A_{PV} measured in elastic electron-proton scattering with a very small probability of $P_{s\bar{s}} = 0.025\%$ for the $uudss$ components. The agreement with G_A^s data can be improved in the low- q^2 region by considering an admixture of configurations I and II with a total $uudss$ probability $P_{s\bar{s}}$ increased to 0.058% with configuration I accounts for 8% of the total. We further find that without removing CM motion, $P_{s\bar{s}}$ would be overestimated by about a factor of four in the case when transition current dominates.

We have also explored the consequence of a recent claim [21], reached from analyzing existing data on $\bar{d}(x) - \bar{u}(x)$, $s(x) + \bar{s}(x)$, and $\bar{u}(x) + \bar{d}(x) - s(x) - \bar{s}(x)$, that $P_{s\bar{s}}$ lies between 2.4 – 2.9%. A small bump in both $G_E^s + \eta G_M^s$ and G_A^s in the region of $q^2 \leq 0.1$ GeV 2 for an admixture of configuration I and II.

It is tempting to conclude, from the results presented above, that the current strangeness form factors experiments seem to indicate that the dominant configuration in which $uudss$ arrange themselves in configuration II, in which $uuds$ is in a completely symmetric spatial state $[4]_X$ with flavor and spin state symmetry of $[31]_{FS}[211]_F[22]_S$. However, there are a few caveats here. First is that the agreement between our results and the existing data is not perfect, to say the least. For example, recent data from A4 at $q^2 = 0.22$ GeV 2 gives a negative value of $G_M^s = -0.14 \pm 0.11 \pm 0.11$. One might also ask whether a nonrelativistic constituent quark model is quantitatively reliable in evaluating the contributions of transition current which is found to be dominant in our calculation but is of a relativistic effect in nature. More study about this issue is clearly needed. Lastly, it is known that configurations of (4,1) clustering and (3,2) clustering, like the meson cloud configuration, are not orthogonal. Then whether (4,1) or (3,2) configuration would be favored might be just a matter of choosing a different basis if it turns out that more precise data will require linear combination of several (4,1) clustering configurations.

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